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Jet Physics in Deeply Inelastic Scattering at HERA *

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Résumé

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1. Introduction

The physics of jets and hadronic final states in deeply inelastic scattering is a promising subject at HERA. Experimental results for jet production have been reported by both the H1 [1] and ZEUS [2, 3] collaborations. Owing to the large accessible range in Q^2 and x_B, two important quantities (among others) can be measured: the running coupling constant $\alpha_s(\mu_r^2)$ and the gluon density $f_g(\xi, \mu_f^2)$†. The classification of hadronic final states according to the number of jets and the idea that experimentally observed jets may be identified with specific parton configurations defined by jet algorithms allow for a direct comparison of experimental data with theoretical predictions. Particularly interesting are (2+1) jet events‡, because on the parton level, in perturbative QCD, the lowest-order process for these events is of $\mathcal{O}(\alpha_s)$, and because the lowest-order diagram where the gluon density comes in is of the type that gives rise to this particular final state.

Jet definitions should fulfil the following three criteria:
(i) the definition should be given in terms of experimentally observable quantities,
(ii) it should be applicable in theoretical calculations in the framework of perturbative QCD (i.e. it has to be infrared-safe and should be easily formulated in terms of Lorentz-invariant quantities), and
(iii) it should be well-suited for the process under consideration, e.g. adapted to the experimental situation.
Algorithms which are presently used are of the following types:
(a) Sterman–Weinberg-type algorithms based on energy and angle cuts [4],
(b) algorithms based on cones in pseudorapidity and azimuthal angle (for an overview, see [5]),
(c) cluster algorithms of the JADE-type [6],
(d) k_T-type algorithms [7, 8].
Algorithms from (a) and (b) are suited for e^+e^- and pp colliders, because they are adapted to specific frames

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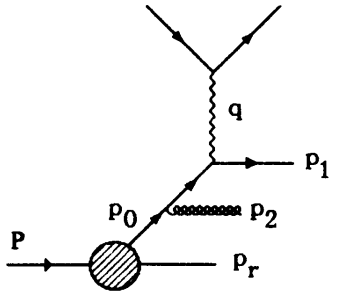

Figure 1. *Feynman diagram giving rise to an initial state singularity*

of reference. In deeply inelastic ep scattering, the CM frame of the QCD subprocess is neither identical with the laboratory system nor related to this frame by a boost along the beam axis alone. A Lorentz-invariant jet definition scheme is therefore preferable, based on algorithms of type (c) and (d). Presently available next-to-leading order (NLO) calculations are based on modifications of the JADE algorithm. k_T-type algorithms are constructed such that even the finite parts of the jet structure functions factorize in the same way as totally inclusive structure functions like F_2 do. This property allows for a resummation of terms $\sim \log E_T^2/Q^2$ and $\sim \log y_{cut}$ [7]. No theoretical NLO calculations for jet cross sections are yet available for k_T-type algorithms, so we return to the discussion of the JADE-type algorithms.

Compared to jet physics in e^+e^- annihilation, there is an additional complication in ep scattering. One of the incoming particles is strongly interacting and thus its remnants give rise to an additional jet. In the perturbative picture, this is related to partons emitted from the incident parton causing an infrared singularity in the collinear phase-space region (see Fig. 1, p_2 collinear to p_r).

The factorization properties of QCD take care of this singularity: all collinear singularities from the initial state can be absorbed in a process-independent way in universal parton distribution functions. A consequence for jet physics is that a resolution criterion must be given which specifies when a parton emitted from the incident parton classifies as an additional jet: the proton remnant has to be included in the jet definition. A complication in the case of a collider experiment is that most of the remnant jet simply disappears in the beam pipe without being seen by the detector. The modified JADE (mJADE) algorithm is defined in the following way [9]:
(1) define a *precluster* of longitudinal momentum p_r given by the missing longitudinal momentum of the event,
(2) apply the JADE cluster algorithm to the set of momenta $\{p_1, \ldots, p_n, p_r\}$, where $p_1, \ldots, p_n$ are the momenta of the visible hadrons in the detector. The resolution criterion is $s_{ij} = 2p_ip_j > cM^2$. Here M^2 is a mass scale and c is the resolution parameter ($c \approx 0.02$). In the case of a theoretical calculation, p_r is directly given by the momentum fraction of the proton not carried by the incident parton, and $p_1, \ldots, p_n$ are the momenta of the partons in the final state. In the following, we choose W^2, the squared total hadronic energy, as the mass scale M^2, since the proton remnant is included in the jet definition.

Based on a specific jet definition scheme, QCD corrections to the leading order (LO) processes can be calculated. An overview will be given in the next section. In Section 3 we describe two applications: The measurement of the running strong coupling constant $\alpha_s(\mu_r^2)$ and the determination of the gluon density $f_g(\xi, \mu_f^2)$ via jet rates. The paper closes with a summary and conclusions.

2. QCD corrections

In the last few years, QCD corrections in NLO for jet production cross sections have been calculated. The case of (1+1) jets is treated in detail in [10]. The NLO corrections to (2+1) jet production for the dominant transverse photon helicity have been calculated in [11, 12, 13]. The remaining helicity cross sections can be found in [14]. The (3+1) jet cross section on the Born level has been determined in [15], and even the (4+1) jet cross section is known [16]. There are presently two programs available which incorporate NLO corrections: DISJET [17] (transverse and longitudinal cross sections, no arbitrary acceptance cuts possible) and PROJET [18] (all helicity cross sections included, an event record allows for arbitrary acceptance cuts). The numerical results presented in the following are based on PROJET.

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Fixed order perturbation theory introduces a scale dependence on the renormalization scale μ_r and factorization scale μ_f. The NLO cross section for e.g. the (2+1) jet final state can be written formally in the form

$$\sigma^{NLO}(\mu_r^2, \mu_f^2) = \int \mathrm{d}\xi\, f(\xi, \mu_f^2) \left\{ \alpha_s(\mu_r^2)\, T_{Born}(\xi) + \left(\alpha_s(\mu_r^2)\right)^2 \left(T_{virt.}(\xi, \mu_r^2) + T_{real}(\xi, \mu_f^2) \right) \right\}. \quad (1)$$

The variation of $\sigma^{NLO}(\mu_r^2, \mu_f^2)$ with μ_r^2 and μ_f^2 is of

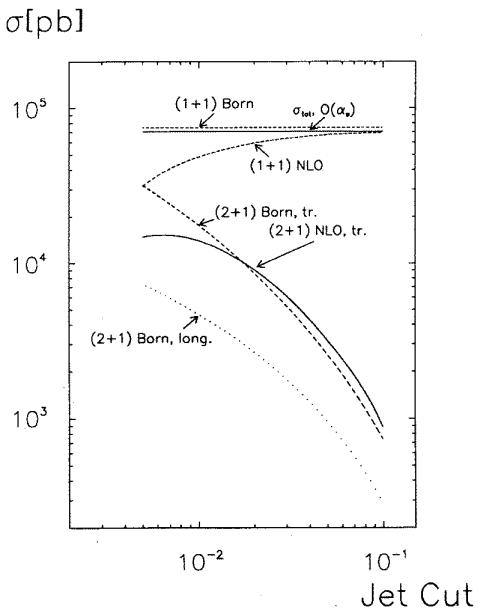

Figure 2. *Jet cut dependence; "tr." and "long." stand for transverse and longitudinal contributions, respectively*

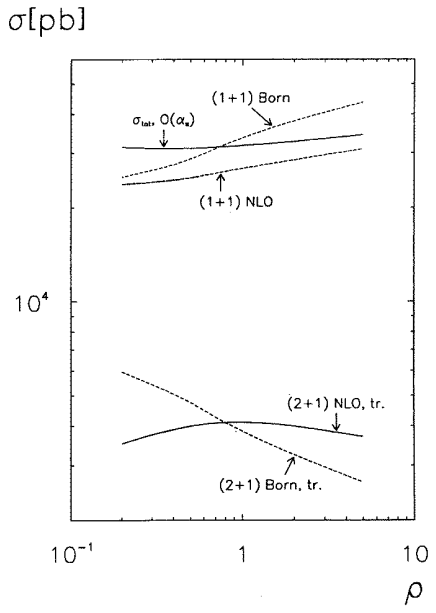

Figure 3. *Scale dependence of jet cross sections*

$\mathcal{O}(\alpha_s^3)$. It is thus expected that the scale dependence of the NLO result is smaller than that of the LO result.

Figure 3 shows this dependence for $\mu_r = \rho Q$, $\mu_f = \rho Q$. The parameters are $E_{CM} = 295\,\mathrm{GeV}$, $5\,\mathrm{GeV} < Q < 100\,\mathrm{GeV}$, $10\,\mathrm{GeV} < W < 295\,\mathrm{GeV}$, $c = 0.02$. The scale dependence of the NLO result is clearly reduced.

The effect on the (2+1) jet rate $R_{2+1} = \sigma_{2+1}/\sigma_{tot}$ is displayed in Fig. 4, where (a), (b) and (c) stand for $\mu_r = \rho Q$, $\mu_f = Q$; $\mu_r = Q$, $\mu_f = \rho Q$; and $\mu_r = \rho Q$, $\mu_f = \rho Q$, respectively.

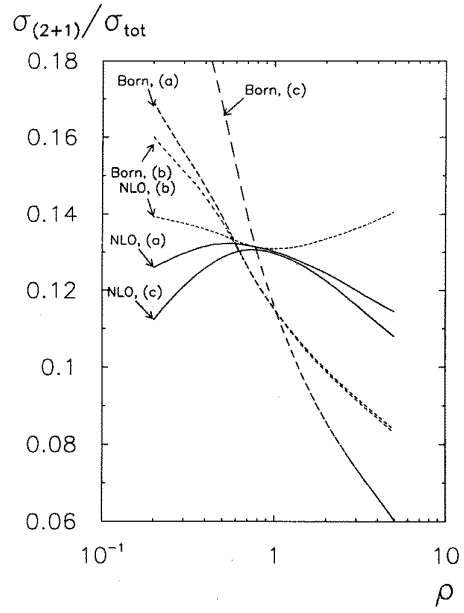

Figure 4. *Scale dependence of the (2+1) jet rate*

3. Applications

We briefly discuss two interesting applications, the measurement of the strong coupling constant and the determination of the gluon density.

In LO, the (2+1) jet rate R_{2+1} is proportional to the strong coupling constant α_s. This makes R_{2+1} an interesting observable, if the hadronization corrections can be controlled. In a recent paper, the H1 collaboration has quoted a value $\alpha_s(M_Z^2) = 0.123 \pm 0.018$ from R_{2+1} [20], consistent with the current world average. One of the major uncertainties of this result is the systematic error from the correction factors from the hadron level to the parton level. More refined jet algorithms which are better adapted to the experimental situation may improve the situation.

In the analysis, it turned out that the forward direction is not yet well understood. Cuts on the polar angle and transverse momentum were imposed in the H1 analysis in order to restrict the phase space variables to a region where the application of fixed order matrix elements is justified [21]. Cuts on the (2+1) jet variable z as used by the ZEUS collaboration in their analysis of jet cross sections have a similar effect [3].

Another challenge is a direct determination of the gluon density via jet rates. It has been pointed out [22] that the gluon density $f_g(\xi, \mu_f^2)$ is not yet well

constrained for $0.01 < \xi < 0.1$. Precisely in this region jet cross sections are sensitive to the parton densities. An experimental analysis is therefore worth while. The gluon density f_g can be reconstructed from

$$R_{2+1}^{exp} = \frac{f_q \otimes \sigma_{2+1,q}^{th} + f_g \otimes \sigma_{2+1,g}^{th}}{f_q \otimes \sigma_{tot,q}^{th} + f_g \otimes \sigma_{tot,g}^{th}} \qquad (2)$$

if the quark densities f_q are known. Recently, first experimental results in LO have been obtained [23]. A feasibility study in LO based on an event generator is available [24]. The applied method is based on a direct reconstruction of the momentum fraction ξ of the incident parton from the final state kinematics. Unfortunately, this simple and straightforward method breaks down in NLO, because then ξ is no longer an observable, due to the redefinition of the parton densities and corresponding finite subtractions. A method which is applicable in NLO and based on the Mellin transform is presently under study [25].

4. Summary and Conclusions

We have given a brief overview of jet physics in deeply inelastic electron–proton scattering with some emphasis on next-to-leading order QCD corrections. The corrections stabilize the theoretical predictions with respect to scale variations and allow for an experimental determination of scale-dependent quantities.

The NLO predictions have already been used for a determination of the running strong coupling constant $\alpha_s(\mu_r^2)$ at HERA. A measurement of the gluon density $f_g(\xi, \mu_f^2)$ in NLO for $\xi > 0.01$ by means of jet rates seems to be feasible as well.

It would certainly be desirable to have NLO predictions for jet cross sections based on other jet definition schemes, such as the k_T-scheme and cone algorithms, as well. As can easily be seen, the mJADE algorithm restricts the accessible range in the momentum fraction ξ of the incident parton to values larger than the jet cut c, if the mass scale used for the jet definition is W^2. In order to be sensible to the gluon density at small ξ, other jet definitions have to be used. Moreover, event-shape variables for ep scattering should be considered as well.

From a physics point of view, the forward (i.e. proton) direction deserves further study. Jet production in this region is not yet well understood, and it is unclear whether fixed order matrix elements can describe the situation at all. A study with event generators shows that the problem probably stems from the emission of partons from the incident parton, modelled by an initial state parton shower. Moreover, the fragmentation of the target remnant jet is poorly understood and contributes to the problem.

Acknowledgements

It is a pleasure to thank the conveners of the working group on Hadronic Final States and the organizing committee.

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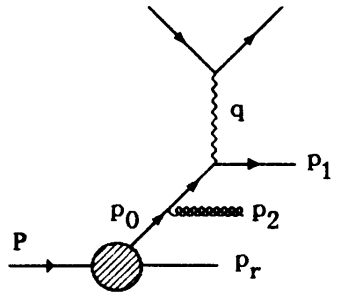

Figure 1. *Feynman diagram giving rise to an initial state singularity*

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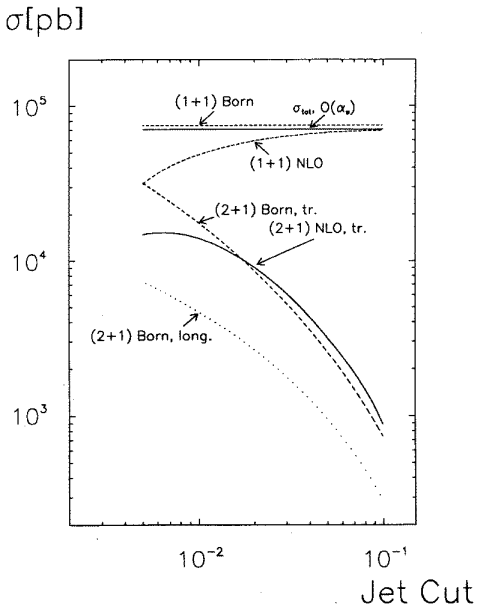

Figure 2. *Jet cut dependence; "tr." and "long." stand for transverse and longitudinal contributions, respectively*

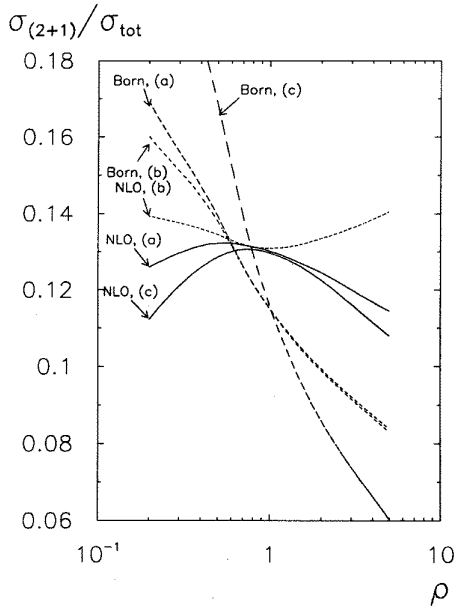

Figure 4. *Scale dependence of the (2+1) jet rate*

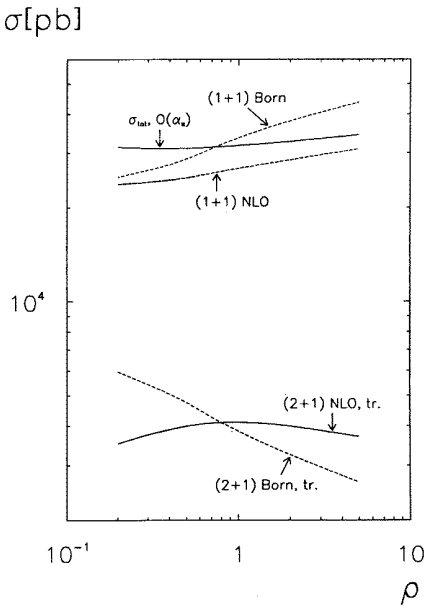

Figure 3. *Scale dependence of jet cross sections*

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We briefly discuss two interesting applications, the measurement of the strong coupling constant and the determination of the gluon density.

In LO, the (2+1) jet rate R_{2+1} is proportional to the strong coupling constant α_s. This makes R_{2+1} an interesting observable, if the hadronization corrections can be controlled. In a recent paper, the H1 collaboration has quoted a value $\alpha_s(M_Z^2) = 0.123 \pm 0.018$ from R_{2+1} [20], consistent with the current world average. One of the major uncertainties of this result is the systematic error from the correction factors from the hadron level to the parton level. More refined jet algorithms which are better adapted to the experimental situation may improve the situation.

In the analysis, it turned out that the forward direction is not yet well understood. Cuts on the polar angle and transverse momentum were imposed in the H1 analysis in order to restrict the phase space variables to a region where the application of fixed order matrix elements is justified [21]. Cuts on the (2+1) jet variable z as used by the ZEUS collaboration in their analysis of jet cross sections have a similar effect [3].

Another challenge is a direct determination of the gluon density via jet rates. It has been pointed out [22] that the gluon density $f_g(\xi, \mu_f^2)$ is not yet well

constrained for $0.01 < \xi < 0.1$. Precisely in this region jet cross sections are sensitive to the parton densities. An experimental analysis is therefore worth while. The gluon density f_g can be reconstructed from

$$R_{2+1}^{exp} = \frac{f_q \otimes \sigma_{2+1,q}^{th} + f_g \otimes \sigma_{2+1,g}^{th}}{f_q \otimes \sigma_{tot,q}^{th} + f_g \otimes \sigma_{tot,g}^{th}} \qquad (2)$$

if the quark densities f_q are known. Recently, first experimental results in LO have been obtained [23]. A feasibility study in LO based on an event generator is available [24]. The applied method is based on a direct reconstruction of the momentum fraction ξ of the incident parton from the final state kinematics. Unfortunately, this simple and straightforward method breaks down in NLO, because then ξ is no longer an observable, due to the redefinition of the parton densities and corresponding finite subtractions. A method which is applicable in NLO and based on the Mellin transform is presently under study [25].

4. Summary and Conclusions

We have given a brief overview of jet physics in deeply inelastic electron–proton scattering with some emphasis on next-to-leading order QCD corrections. The corrections stabilize the theoretical predictions with respect to scale variations and allow for an experimental determination of scale-dependent quantities.

The NLO predictions have already been used for a determination of the running strong coupling constant $\alpha_s(\mu_r^2)$ at HERA. A measurement of the gluon density $f_g(\xi, \mu_f^2)$ in NLO for $\xi > 0.01$ by means of jet rates seems to be feasible as well.

It would certainly be desirable to have NLO predictions for jet cross sections based on other jet definition schemes, such as the k_T-scheme and cone algorithms, as well. As can easily be seen, the mJADE algorithm restricts the accessible range in the momentum fraction ξ of the incident parton to values larger than the jet cut c, if the mass scale used for the jet definition is W^2. In order to be sensible to the gluon density at small ξ, other jet definitions have to be used. Moreover, event-shape variables for ep scattering should be considered as well.

From a physics point of view, the forward (i.e. proton) direction deserves further study. Jet production in this region is not yet well understood, and it is unclear whether fixed order matrix elements can describe the situation at all. A study with event generators shows that the problem probably stems from the emission of partons from the incident parton, modelled by an initial state parton shower. Moreover, the fragmentation of the target remnant jet is poorly understood and contributes to the problem.

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